Biological Effects of Radiation

- Interaction of ionizing radiation with the human body can arise from:
  - External sources outside the body
  - Internal contamination of the body by radioactive substances
- Leads to biological effects that may show up later as clinical symptoms
- The nature and severity of the symptoms and the time at which they appear $\propto$ the amount of radiation absorbed and the rate at which it is received

Biological Effects

The biological effects may appear in:

1. The person receiving the radiation dose
   - These are called SOMATIC effects
2. Later generations due to radiation damage to the germ cells in the reproductive organs (the gonads)
   - These are called HERITABLE effects

Basic Human Physiology

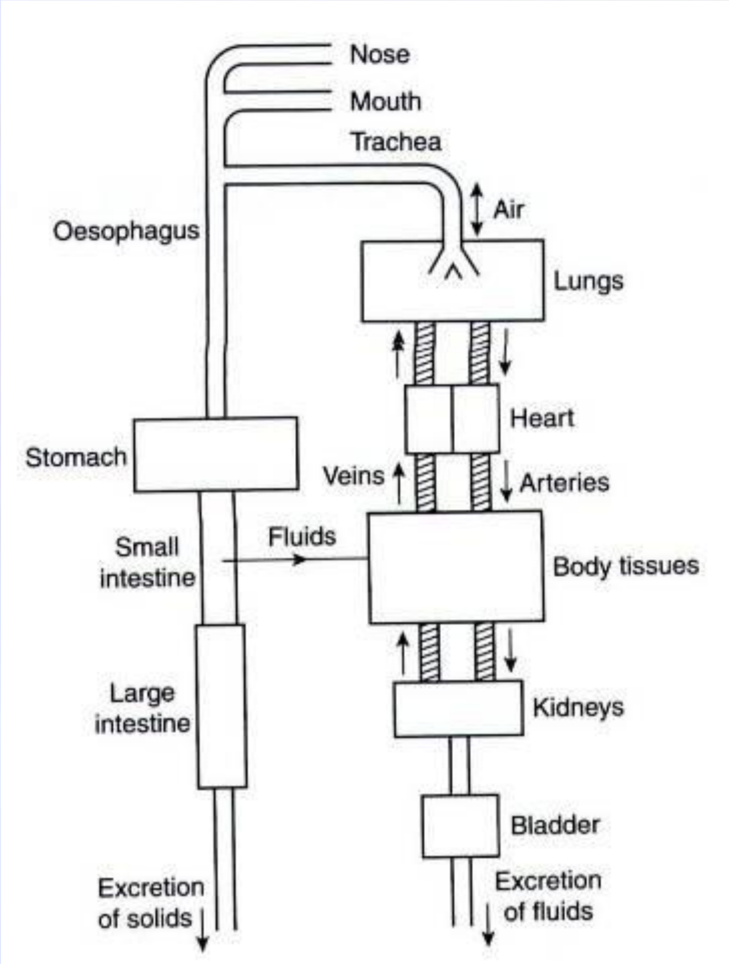
- A knowledge of physiology is necessary to understand the ways in which radioactivity can enter and become distributed in the body
- The human systems which are most relevant to an understanding of the behaviour of radioactive substances which enter the body are:
  - The CIRCULATORY system
  - The RESPIRATORY system
  - The DIGESTIVE system

The Circulatory System

- A closed circuit of tubes around which the blood is pumped by the action of the HEART
- Blood is the transport mechanism of the body. It circulates to almost every region carrying nutrients (from food) and oxygen to the cells
- Also, it picks up waste products and carbon dioxide and transfers them to the excretory organs
- The body contains about 5 litres of blood which circulates about once a minute

The Circulatory System

- The heart is two pumps
- Left side pumps blood through the arteries to the tissues
- Nutrients transferred from tissues to cells via tissue fluid
- After passing through tissues blood returns to right side of heart via veins
- Blood then pumped to the lungs where it becomes oxygenated before returning to the left side of the heart



Blood

- Arterial blood – oxygenated and bright red
- Venous blood – de-oxygenated and dark red with a bluish tinge
- Three types of blood cells:
  - Red cells (erythrocytes)
    - transport the food and oxygen required by the body
  - White cells (leukocytes)
    - defend against infection by digesting foreign micro-organisms
  - Platelets (thrombocytes)
    - play a vital role in the formation of clots at the site of injuries

The Respiratory System

- Respiration (or breathing) is the method by which oxygen is taken into the lungs and carbon dioxide eliminated
- The volume of air breathed per day is ~ 20 m^3
- Half of this is considered to be breathed during the 8 h of work
- During respiration, airborne contamination can be inhaled in the form of:
  - Gaseous materials
  - Particulate materials (e.g. airborne dust or smoke)

The Respiratory System

- Gases:
  - pass freely into lungs and enter bloodstream to an extent which depends on their solubility
- Particulates:
  - only a fraction of inhaled material is deposited in lungs; remainder is either exhaled or deposited in the upper respiratory passages and subsequently swallowed
- Soluble materials:
  - absorbed into bloodstream in a few hours
- Insoluble materials:
  - may persist in the lungs for many months

The Digestive System

- The digestive tract consists of:
  - the oesophagus
  - the stomach
  - the small intestine
  - the large intestine
- Food converted into:
  - A form suitable for production of energy and heat
  - Molecules necessary for growth and repair
  - Large molecules – broken down by enzymes before being absorbed into the bloodstream and passed via the liver to the tissues

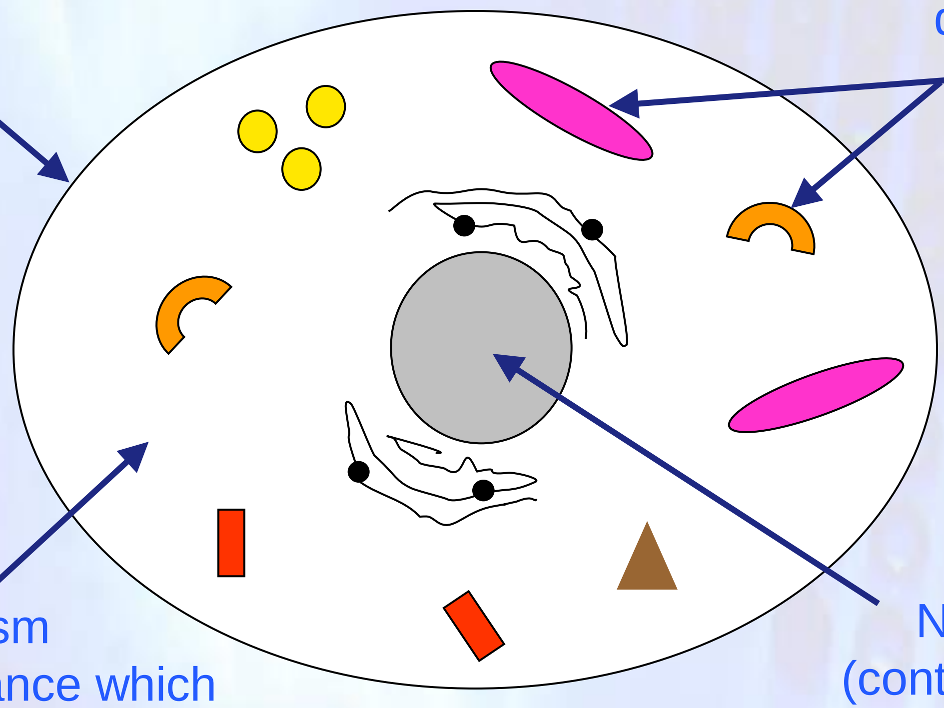
The Digestive System

- Solid waste (faeces) – unabsorbed food + bacteria + cells shed from intestine walls
- Liquid waste (urine) – waste products of cells dissolved in water – excreted via kidneys and bladder

The Digestive System

- Soluble radioactive contamination (when swallowed):
  - Passes through the walls of the digestive tract
  - Absorbed into the bloodstream
  - Distributed to all parts of the body
  - Can concentrate mainly in some specific organ or tissue, and irradiate it until it decays or is excreted
- Insoluble radioactive contamination:
  - Passes through the digestive tract and is excreted in the faeces
  - During its passage through the body it will irradiate the tract and the large intestine

The Human Cell



Cell Biology

- Cytoplasm – the 'factory' of the cell
  - Contains various sub-structures (called organelles) which break down food nutrients and convert them into energy and smaller molecules
  - Smaller molecules are later converted into complex molecules needed by the cell for maintenance or duplication
- Nucleus – the 'information centre' of the cell
  - Normally contains 46 chromosomes – tiny threadlike structures made up of genes
  - Genes consist of deoxyribonucleic acid (DNA) and protein molecules
  - Carry the information which determines the characteristics of the daughter cell

Cell Reproduction

- Cells are able to reproduce to compensate for cells that die
- Different types of human cells have different life-cycles which vary from hours to years

Cell Reproduction

There are TWO ways for cell reproduction:

- MITOSIS - reproduction of ordinary cells
  - the chromosomes duplicate by splitting lengthways
  - the original cell then divides into two new cells, each ‘daughter’ is identical to the original ‘parent’ cell
- MEIOSIS – reproduction of sperm and ovum cells
  - in sexual reproduction the sperm + ovum combine
  - chromosomes combine to form a new different cell with genes from each of the parent cells

Interaction of Radiation with Cells

- Cells are largely composed of water
- Nuclear radiations can cause ionization
- Ionisation of cellular water can lead to molecular changes and the formation of chemicals that can damage chromosomes
- Leads to changes in the structure and function of the cell which can manifest themselves as clinical symptoms such as sickness, cataracts or cancer
- Overall process is usually considered to occur in FOUR STAGES (1 to 4 in next slides)

1 - Physical Stage

- Lasts for only an extremely small fraction (approximately 10^{-16}) of a second
- Radiation energy is deposited in the cell water and causes ionization

$$H_2O \xrightarrow{\text{radiation}} H_2O^{+} + e^{-}$$

Positive ion

Negative ion (electron)

2 - Physiochemical Stage

- Lasts about 10^{-6} second
- Ions interact with other water molecules resulting in a number of new products e.g. the positive ion dissociates

$$H_2O^+ \longrightarrow H^+ + OH$$

- The electron attaches to a neutral water molecule which then dissociates

$$H_2O + e^- \longrightarrow H_2O^-$$

$$H_2O^- \longrightarrow H + OH^-$$

2 - Physiochemical Stage

- H^+ and OH^- are present to a large extent in ordinary water, and take no part in other reactions
- H and OH have an unpaired electron. They are called 'free radicals' and are very reactive
- Another reaction product is hydrogen peroxide, H_2O_2, which is a strong oxidizing agent and formed by the reaction:

$$OH + OH \longrightarrow H_2O_2$$

3 - Chemical Stage

- Lasts a few seconds
- Reaction products from previous stage interact with important molecules in the cell
- The free radicals and oxidizing agents attack the complex molecules that form chromosomes
- They may, for example, attach themselves to a molecule or cause links in long chain molecules to be broken

4 - Biological Stage

- May vary from 10’s of minutes to 10’s of years depending on the symptoms
- Chemical changes can affect the cell in a number of ways
- For example they may result in:
  - the early death of the cell, or the prevention or delay of cell division; or
  - a permanent modification which is passed on to daughter cells

Cell Death or Prevention of Division

- Leads to depletion of the cell population within organs of the body
- Below a certain level of dose (a threshold), the proportion of cells damaged is not sufficient to affect the function of the organ and there will be no observable effect on the organ or the body as a whole
- Above the threshold, effects will start to be observed and the severity of the effects will increase quite rapidly as the dose increases
- Formerly called DETERMINISTIC effects
- Now use the term HARMFUL TISSUE REACTIONS

Cell Modification

- Modification passed on to daughter cells
- After a latency period, may result in a cancer in the person exposed to the radiation (somatic effects)
- If modification is to a reproductive cell, the damage may be transmitted to later generations (heritable effects)
- In these cases, it is the likelihood of the effect occurring that goes up as the dose increases
- These are called stochastic effects (meaning ‘of a random or statistical nature’)

Harmful Tissue Reactions

- Acute Radiation Effects
  - Acute exposure – is a large dose over a relatively short period of time
  - Occur within a few weeks after exposure
  - Main effects are due to bone marrow, gastrointestinal or neuromuscular damage, depending on the dose received, caused by cell depletion
  - Acute absorbed doses above about 1 Gy (Gray) cause nausea and vomiting (radiation sickness). It occurs a few hours after exposure as a result of damage to cells lining the intestine and H_2O_2 formation
  - Absorbed doses > 3 Gy can lead to death – probably 10–15 days post exposure

Harmful Tissue Reactions

- Acute Radiation Effects
  - Region of infection death: doses range from 3 to 10 Gy. Special medical treatments (e.g. sterile environment and bone marrow transfusion) can increase chances of survival
  - Region of gastrointestinal death: for doses > 10 Gy survival time drops abruptly to between 3 to 5 days. Gross damage to lining of intestine followed by severe bacterial invasion
  - Region of central nervous system death: for doses >> 10 Gy survival time is much shorter

Harmful Tissue Reactions

- Acute Radiation Effects
  - Erythema (skin reddening) is another effect which shows up soon after acute exposure
  - In many situations the skin is subject to more radiation exposure than most other tissues, especially for betas and low-energy x-rays
  - Approximately 3 Gy low-energy x-rays will cause erythema
  - Larger skin exposures may lead to blistering and ulceration

Radiation Burns

Damage to the hands from high-dose x-ray exposure

Harmful Tissue Reactions

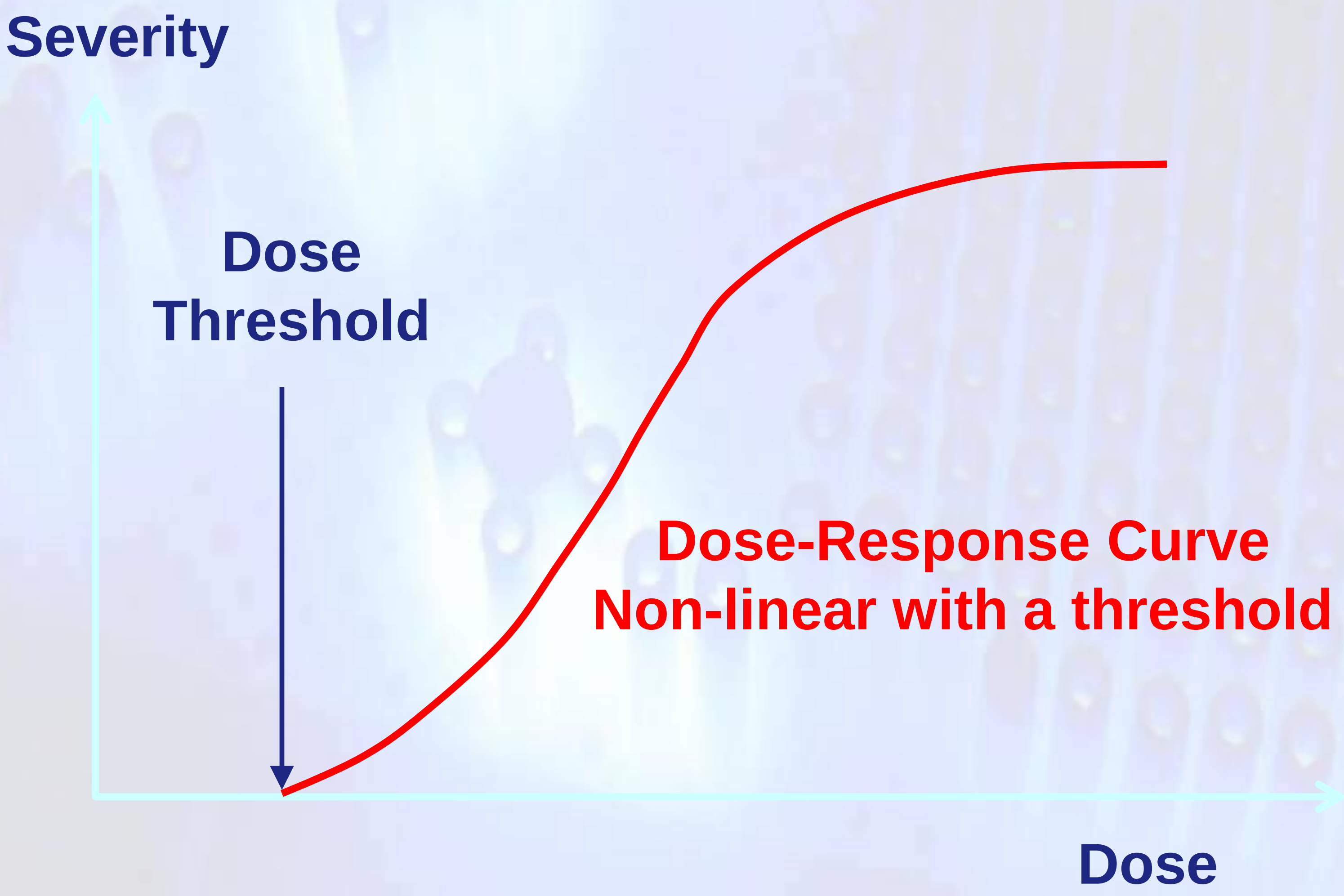
- Acute Radiation Effects
  - Levels of dose to workers and public from normal operations in the nuclear industry, other industrial applications and most medical uses, are far below what could induce early effects
  - Such high doses, and therefore early effects, could only occur in an unlikely accident
  - Some early effects (e.g. skin erythema) are seen in patients undergoing external beam radiotherapy to treat a cancer
  - The low doses received in normal operations may cause long term effects

Harmful Tissue Reactions

- Late Tissue Effects
  - Opacity in the lens of the eye
  - May not occur for many years
  - In extreme cases can lead to visual impairment as a result of a cataract
  - Here again, there is a threshold dose and so, by setting a dose limit for the lens of the eye, the occurrence of these effects can be prevented
  - Cataractogenesis, and the appropriate threshold dose, is currently the subject of much international debate in the radiation protection profession

Harmful Tissue Reactions

Also include: hair loss, sterility, bleeding gums etc.



Stochastic Effects – Cancer

- Cancer is an over-proliferation of cells in a body organ
- Defect in ‘control system’ of the cell (in DNA) that makes it divide more rapidly
- Defect is transmitted to daughter cells so the population of abnormal cells builds up to the detriment of the normal cells in the organ

Stochastic Effects – Cancer

- Estimates of risk of cancer induction due to radiation are complicated by:
  - Long and variable latency periods
  - Radiation-induced cancers indistinguishable from other cancers caused by, say, tobacco smoke
  - High background rate of cancer occurrence

Stochastic Effects – Cancer

- ICRP estimate that, averaged over a population of all ages, a whole body dose of 1 Sv would result in a radiation-induced fatal cancer in about 10 per cent of the persons exposed
  - 1 Sv $\rightarrow$ 1 in 10 (or 0.1) chance of a fatal cancer
- Linearly extrapolating down to low doses (those typically encountered in industry etc.) gives:
  - 1 mSv $\rightarrow$ 1 in 10,000 (or 0.0001) chance of a fatal cancer
- BUT this is likely to be an overestimate by a factor of 2 (based on Dose and Dose Rate Effectiveness Factor (DDREF) = 2), and so:
  - Risk coefficient is 0.05 per Sv
  - Sometimes written as 5% per Sv or $5 \times 10^{-2}\ Sv^{-1}$

Stochastic Effects – Cancer

- Risk = Dose (Sv) × risk coefficient (Sv^{-1})
- For a dose of 10 mSv (0.01 Sv), the risk of fatal cancer would be:

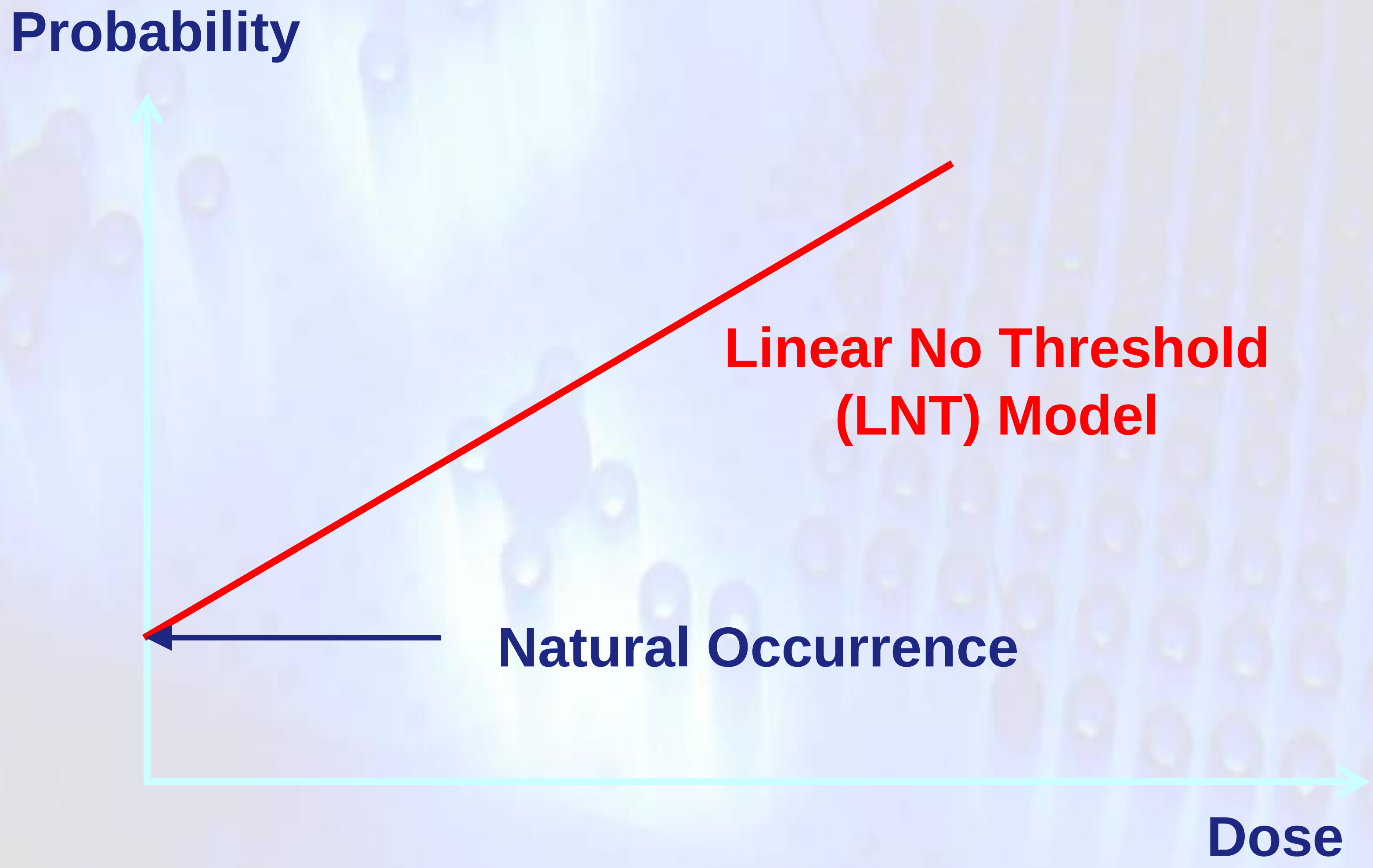
$$\text{Risk} = 0.01\ \text{Sv} \times 5 \times 10^{-2}\ \text{Sv}^{-1} = 5 \times 10^{-4}\ \text{Sv}^{-1}$$

- Note that radiation-induced non-fatal (or curable) cancers need to be taken into account, and this has led to the concept of detriment

Stochastic Effects – Heritable

- Result from damage to the reproductive cells
- Damage causes alterations (genetic mutations) in the hereditary material of the cell
- Radiation can induce gene mutations which are indistinguishable from naturally occurring mutations
- Damage to dominant genes tend to give 1st generation disorders whereas damage to recessive genes may lead to problems in later generations
- Only radiation exposure of gonads up to reproductive age (about 30 years) is important
- ICRP – risk is about 0.2×10^{-2} per Sv for the whole population

Stochastic Effects



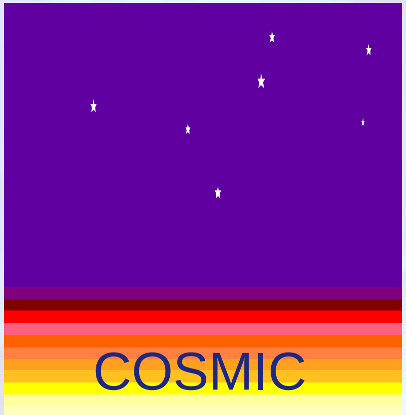
Natural and Man-Made Radiation

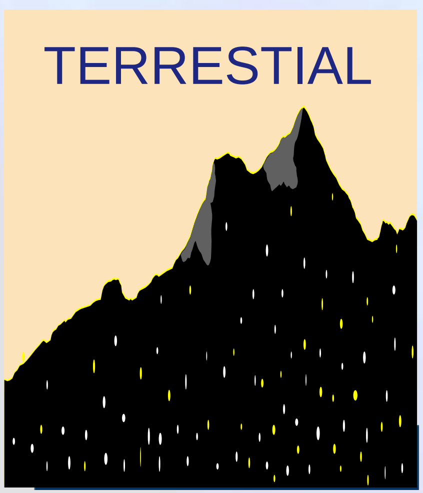
- Natural background radiation comes from two main sources:
  - Cosmic radiation (from sun and outside the solar system)
  - ‘Primordial’ radiation from terrestrial sources

NOTE: Both of these sources can lead to radioactivity within the body

- Man-made (or artificial) sources of radiation have been introduced since:
  - X-rays and radioactivity – discovered at end of 19th century
  - Nuclear fission processes – exploited since middle of 20th century

Natural





About
2.2 mSv/year
in UK

Cosmic Radiation

- Reaches Earth mainly from the Sun but also from interstellar space
- Very wide range of penetrating radiations which undergo many types of reactions with the elements in the atmosphere
- The atmosphere acts as a shield and drastically reduces the amount of cosmic radiation reaching the Earth’s surface
  - Dose rate at sea level ≈ 0.2 mSv / year
  - Dose rate at 3000m altitude ≈ 1mSv / year

Carbon-14

- Interaction of cosmic radiation neutrons with nitrogen in the upper atmosphere produces carbon-14

$$^{14}N\ (n, p)^{14}C$$

- ^{14}C has a half-life = 5568 years
- Diffuses to lower atmosphere and becomes incorporated into living matter e.g. plants and then into the food chain
- Similarly, very small amounts of ^{41}Ca, ^{36}Cl and ^{3}H are maintained in lower atmosphere by cosmic radiation

Terrestrial Radiation

- Rocks and soil of the Earth's strata contain small quantities of the radioactive elements uranium and thorium with their daughter products
- Concentration varies considerably depending on the type of rock formation
- In sandstone and limestone regions the concentration is much lower than in granite
- So dose rate depends location
- In UK, the average effective dose of γ radiation from this source is about 0.35 mSv/year (but may be several times higher in some areas)
- Such radioisotopes may become incorporated into building materials e.g. bricks

NORM

- Naturally Occurring Radioactivity Materials in rocks and soil also means that most natural materials are slightly radioactive
  - NORM is everywhere – in our bodies, in our food, in the ground, in building materials, in products etc

NORM

- Some industrial practices (e.g. oil/gas industry, metal ore smelting, mining etc.) involving natural resources concentrate these radionuclides to a degree that they may pose risk to humans and the environment if they are not controlled
- Technologically-Enhanced NORM (or TENORM) is found in many waste streams e.g. scrap metal, sludges, scales

Radioactivity in the Body

- Ingestion and inhalation of naturally occurring radionuclides gives rise to a dose which varies considerably depending on
  - Location, diet, and the habits of the person
- ^{40}K + isotopes of uranium and thorium series contribute most to this dose
- Of ordinary foods, cereals have a high radioactive content while milk product, fruit and vegetables have a low content
- Biggest contribution to natural background comes from breathing RADON gas

Radon

- Radon is a colourless and odourless gas
- It comes from the radioactive decay of the tiny amounts of natural uranium and thorium in rocks, soils and many building materials
- Most important is ^{222}Rn which is a member of the uranium series
- Radon is the single largest contributor to background radiation dose
- Daughter products of radon attach to dust particles which, when breathed in, irradiate the lung with alpha particles and increase the risk of lung cancer

Radon

- Radon diffuses from the ground and building structures to give a measurable, but not problematic, concentration in the atmosphere in the open air
- Higher, problematic, concentrations can occur within buildings, partly as a result of diffusion from the structural materials but also because radon from the ground can enter the building
- Concentration varies with geographical location depending upon the uranium content of the underlying geology

Radon in Buildings

- Atmospheric pressure indoors is often slightly lower than that outside, especially in the winter
- Radon gas from the ground is drawn into the building through cracks in the floor, shrinkage gaps between the floor and the walls, as well as any service ducts
- Restricted ventilation will increase radon concentrations, and as radon is heavier than air it sinks into cellars or basements
- Note: radon dissolves readily in water and can be found in natural spring or mineral waters from so-called ‘radon affected areas’

Radon in Buildings

- The simplest way to reduce ingress of the radon is by:
  - Sealing walls and floors
  - Increasing the ventilation

- It may be necessary to fit a ‘radon sump’ to vent the gas into the atmosphere outside the building
- A sump has a pipe connecting a space under a solid floor to the outside, and a small electric fan in the pipe continually sucks the radon from under the building and expels it harmlessly to the atmosphere

Passive Radon Meter

- Measurement using ‘passive’ radon meters provides a reliable and simple approach
- Placed in buildings for ~ 3-month period

Passive Radon meter
(from Health Protection Agency)

- Contains a sensitive plastic that registers damage tracks when exposed to alpha particles
- Counting the tracks under a microscope gives the average radon level during the 3 months

Diagnostic Radiology

- Over 90% of total population exposure from man-made sources of ionising radiation is from the diagnostic use of X-rays

- Most important organs are:
  - Bone marrow – damage to primitive blood-forming cells → leukaemia
  - Colon – rapid cell regeneration of epithelium
  - Gonads – irradiation → heritable effects, but far less radiosensitive than previously thought
  - Foetus – irradiation of pregnant patients is very strictly controlled in order to reduce chances of birth defects

Therapy Radiology

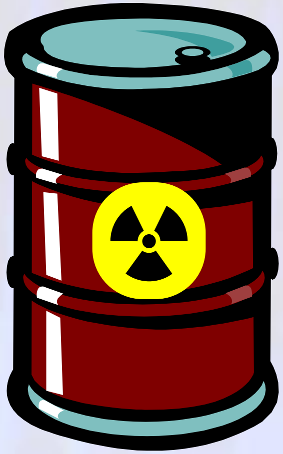
- Average dose (or collective dose) to the population is far less than diagnostic uses
- Individual exposures used in certain treatments may be thousands of times larger than those typically delivered in diagnostic radiography
- BUT the number of people having radiotherapy treatment is much smaller

Use of Radioisotopes

- Use of Radioisotopes (Nuclear Medicine)
  - Gamma-emitting radioisotopes are used in medicine to give a means of tracing the path and location of specific chemicals in the body
  - Using suitable detectors (e.g. so-called ‘gamma cameras’), the behaviour of the active, isotopes of the element may be determined
  - At much higher concentrations, unsealed radioisotopes can be used for therapeutic purposes

Radioactive Waste

- The increasing use of radioisotopes and the development of nuclear power have resulted in an ever-growing quantity of radioactive waste



- Disposal of low level radioactive waste to the environment BUT this is very strictly controlled
- Members of the general population do receive radiation exposure from this source
- At present the average dose to members of the population from waste disposal is very low – only about 1 μSv/year

Atmospheric Fall-Out

- After WW2, several countries did atmospheric nuclear weapons tests
- Radioactive material from bombs was ejected into the stratosphere, distributed around the world, and settled on the ground

From MIT OCW

- Contaminated food $\rightarrow$ public exposure
- Main nuclides
  - ^{90}Sr (½ life = 28.8 yrs – concentrates in bone)
  - ^{137}Cs (½ life = 30 yrs – whole body)

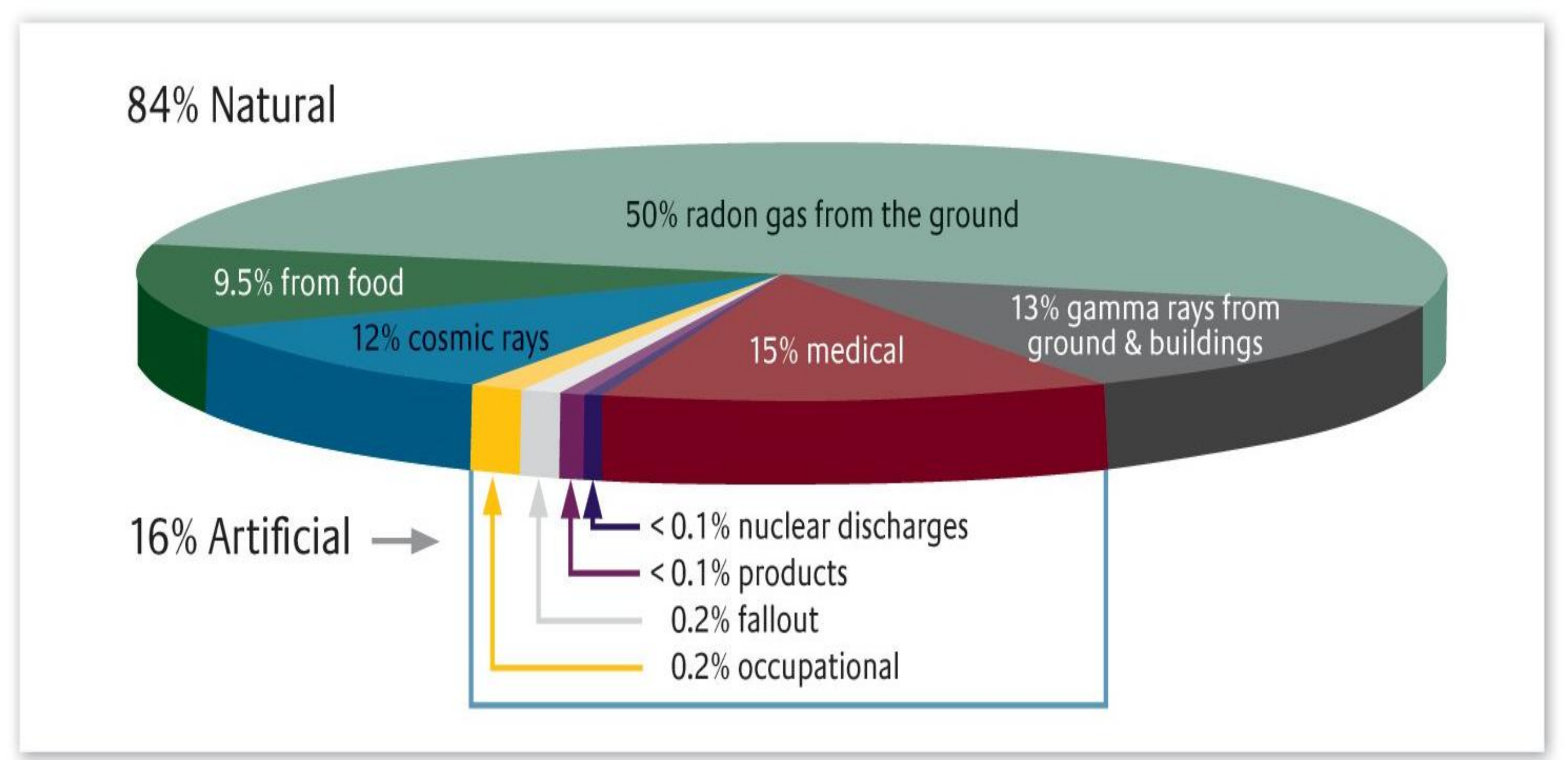
Occupational Exposure

- Doses from all occupational exposure, mainly in medicine, industry and research, is very small when averaged over the whole population
- Average dose in the UK is about 6 μSv/year
- Nuclear power workers contribute 40% of this collective dose with most of the rest coming from the medical sector

Summary of Man-Made Sources

Source	Dose (mSv / year)
Diagnostic radiology	0.38
Therapeutic radiology	0.03
Radioactive waste	0.001
Fall-out from nuclear weapons	0.006
Occupational	0.006
Other	0.005
TOTAL	~ 0.42

Summary



From Health Protection Agency